Drift Chamber with Cluster Counting for CEPC

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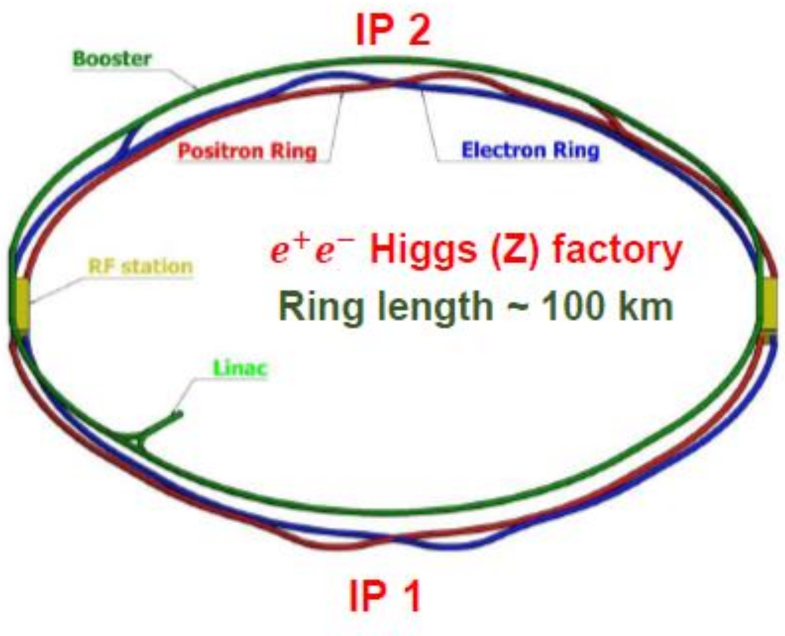
Outline

- Introduction
- Detector optimization
- Reconstruction algorithm for CC
- Prototype experiments
- Summary

The Circular Electron Positron Collider (CEPC)

- The CEPC was proposed in 2012 right after the Higgs discovery. It aims to start operation in 2030s, as an e^+e^- Higgs / Z Factory.
- To produce Higgs / W / Z / top for high precision Higgs, EW measurements, studies of flavor physics & QCD, and probes of physics BSM.
- It is possible to upgrade to a pp collider (SppC) of $\sqrt{s}$ ~ 100 TeV in the future.



Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. /yr (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.
** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.
*** Calculated using 3,600 hours per year for data collection.

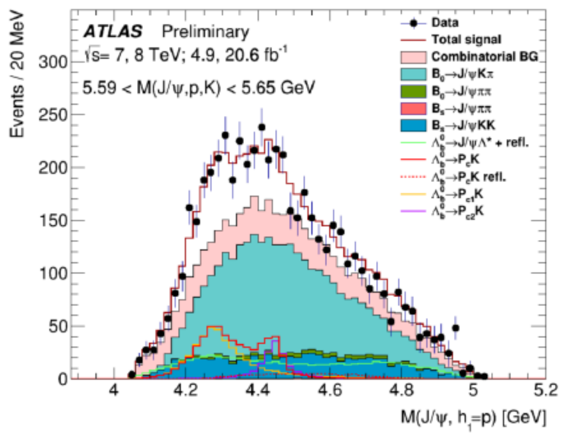
Particle identification

- **PID is essential for CEPC, especially for flavor physics**
  - Suppressing combinatorics
  - Distinguishing between same topology final-states
  - Adding valuable additional information for flavor tagging of jets
  - …

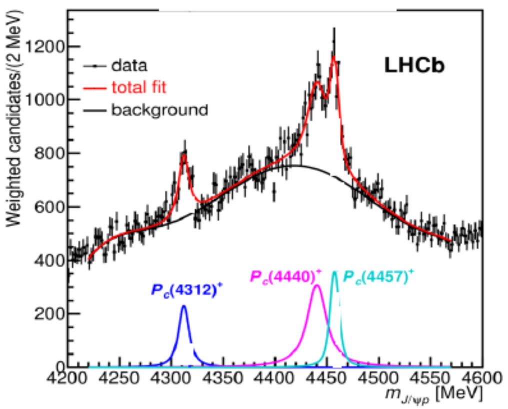
Pentaquark search in $\Lambda_b \to J/\Psi pK$

Without PID

[ATLAS-CONF-2019-048]

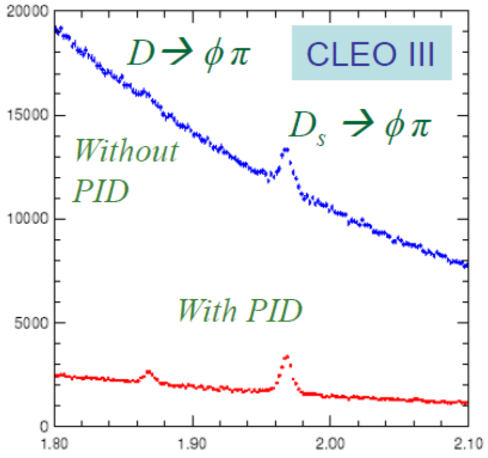


With PID ~ no background



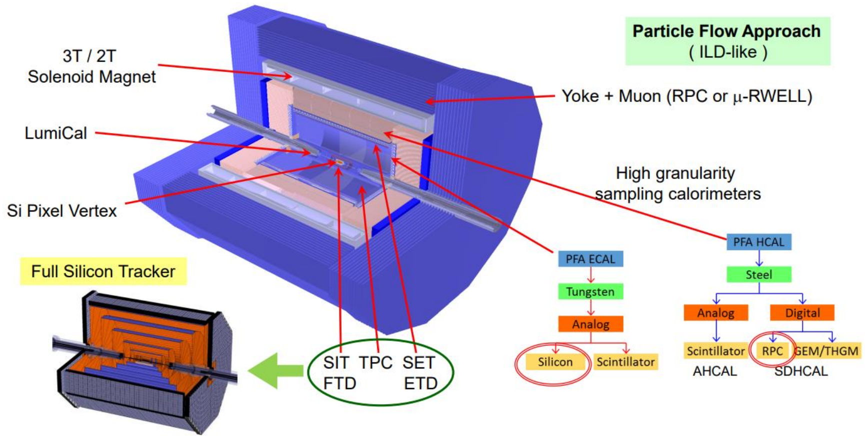
[LHCb, PRL 122 (2019) 222001]

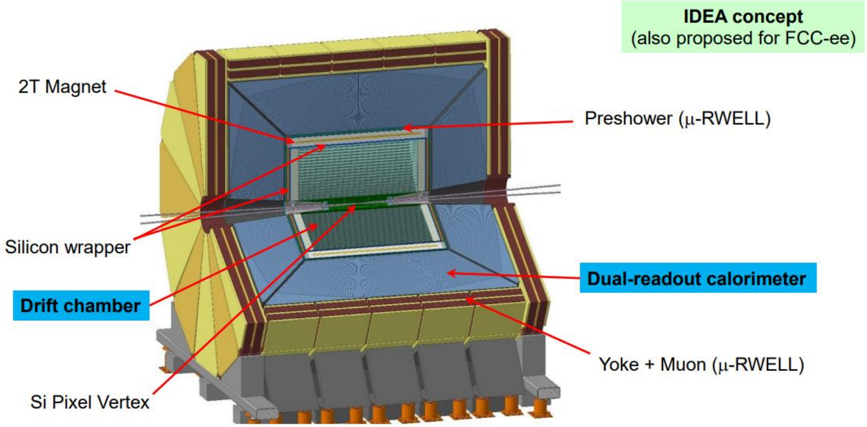
$D_{(s)} \to \phi\pi$



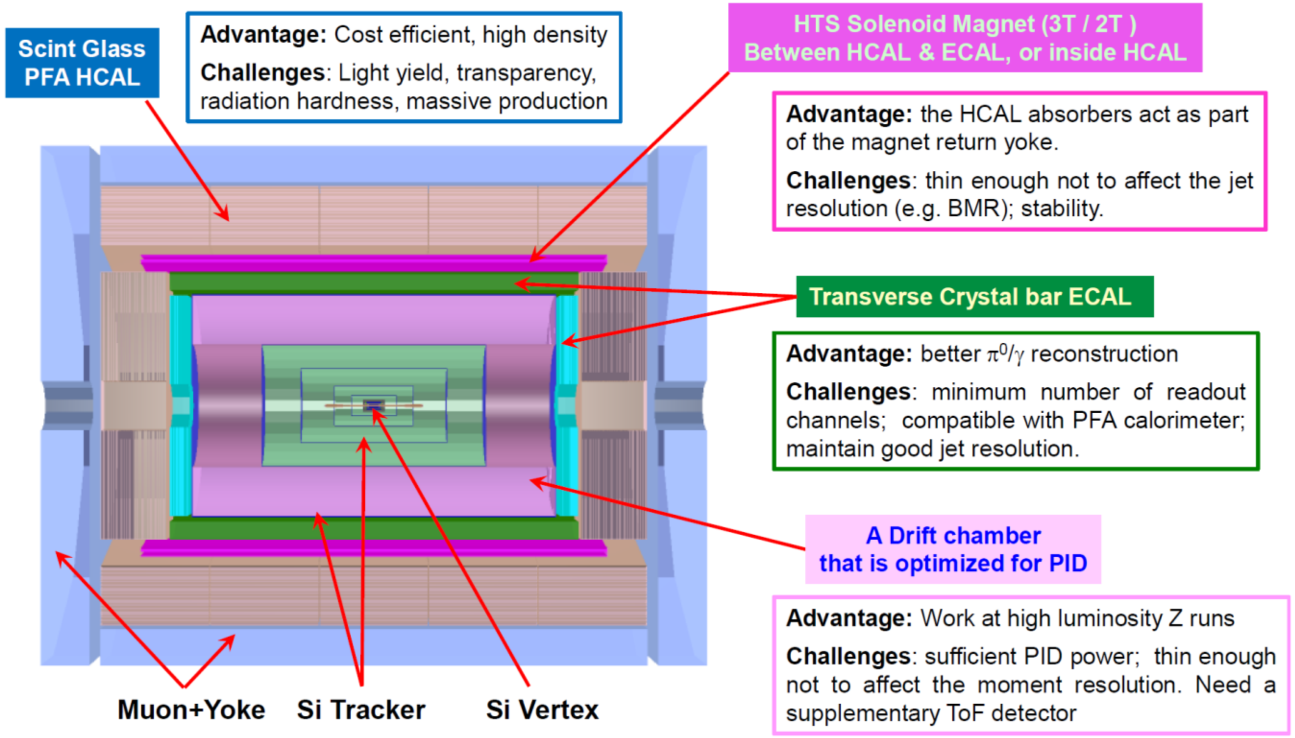
* Figures from Guy Wilkinson's slides

CEPC detector concepts



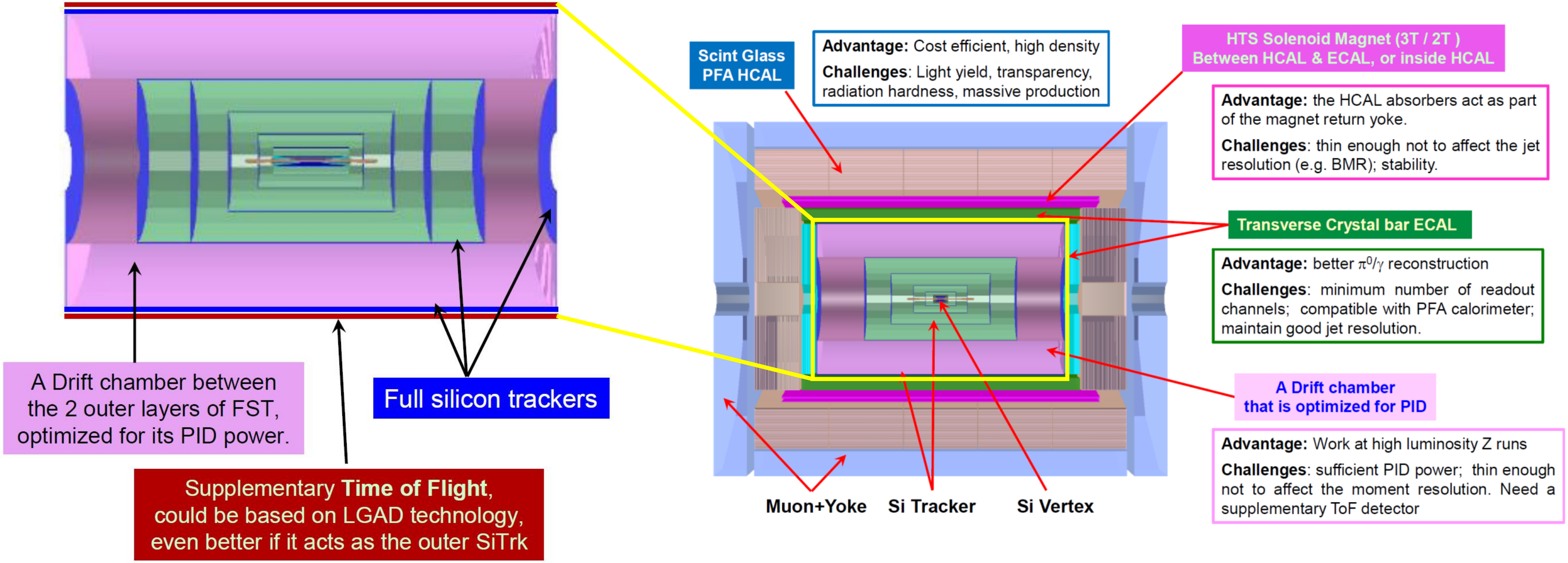


CEPC 4th concept



➔ See yesterday's talk from Nikola for IDEA DC

CEPC 4th concept detector

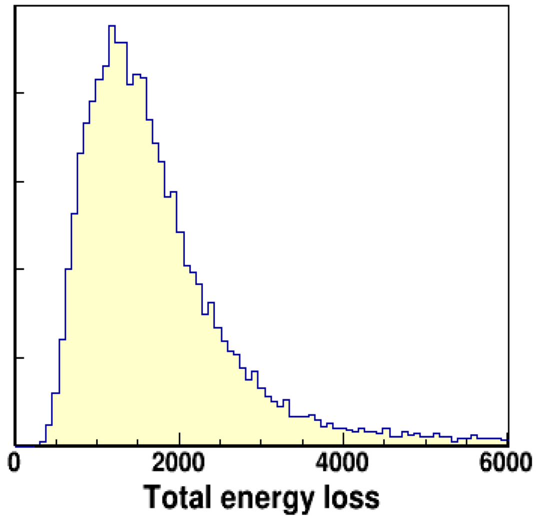


Preliminary PID requirement: >2σ K/π separation for 20 GeV/c tracks

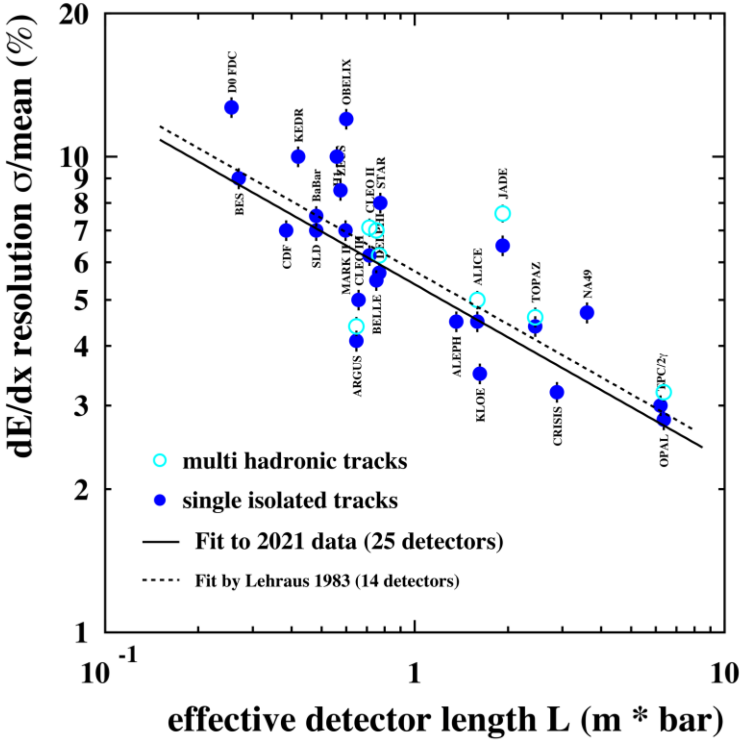
Energy loss measurement: dE/dx

- **Main mechanism: Ionization of charged tracks**
- **Traditional method: Total energy loss (dE/dx)**
  - Landau distribution due to secondary ionizations
  - Large fluctuation from many sources: energy loss, amplification …

Integrated charge



"Lehraus" Plot 2021*



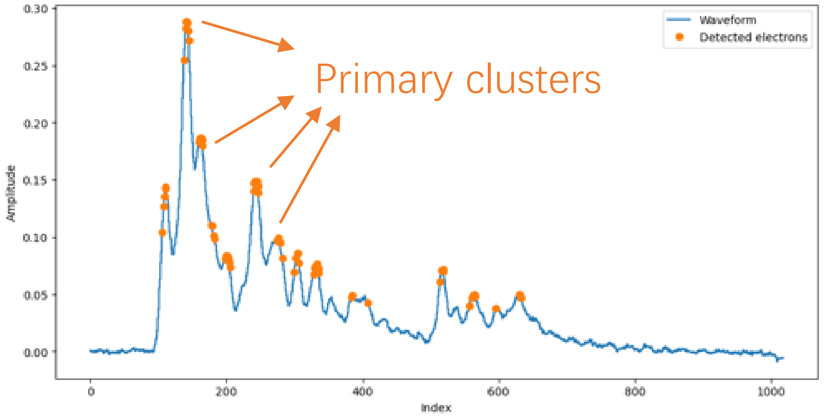
- **Fit by Lehraus 1983:**
  - dE/dx res. = **5.7** $* L^{-0.37}$ (%)
- **Fit in 2021:**
  - dE/dx res. = **5.4** $* L^{-0.37}$ (%)
- **No significant improvement in the past 40 years**

* From Michael Hauschild's talk @ RD51 workshop

Cluster counting measurement (CC)

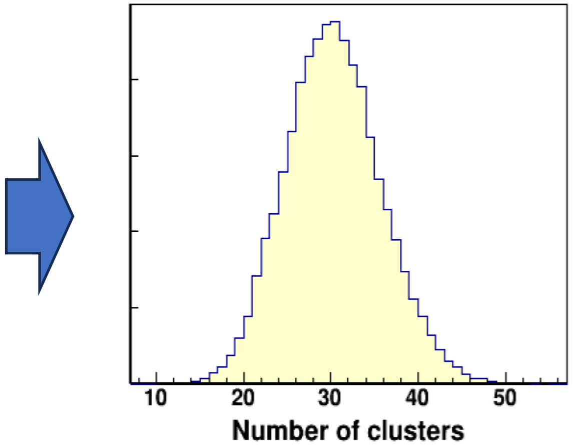
- **Alternatively, counting primary clusters**
  - Poisson distribution ➔ Get rid of the secondary ionizations
  - **Small fluctuation ➔ Potentially, a factor of 2 better resolution than dE/dx**

Waveform

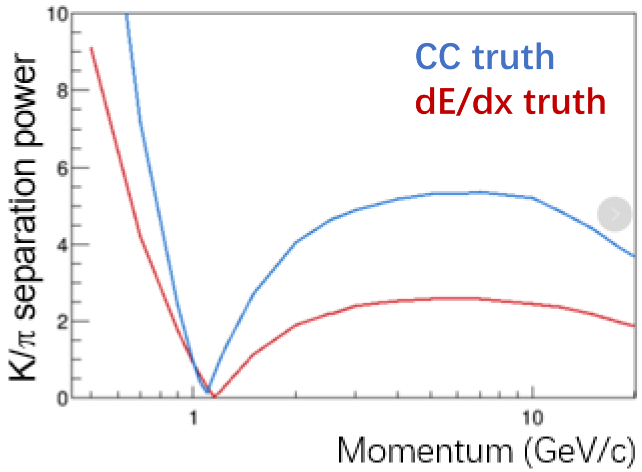


Require fast electronics and sophisticated counting algorithm

Counting clusters



K/π separation power
CC vs dE/dx



CC is extremely powerful, proposed in ILC, FCC-ee, CEPC

Challenges for DC with CC

- **Challenges for cluster counting**
  - Detector design: Detector layout, cell size, working gas with low drift velocity, low ionization density, low diffusion and low cluster size
  - Fast electronics: Bandwidth > 1 GHz, gain > 10, sampling rate > 1.5 GS/s, bit resolution > 12 bit

  → Detector optimization; Prototype experiments

  - Reconstruction: Efficient primary clusters detection from waveforms in high pile-up and noisy environments

  → Deep learning algorithm

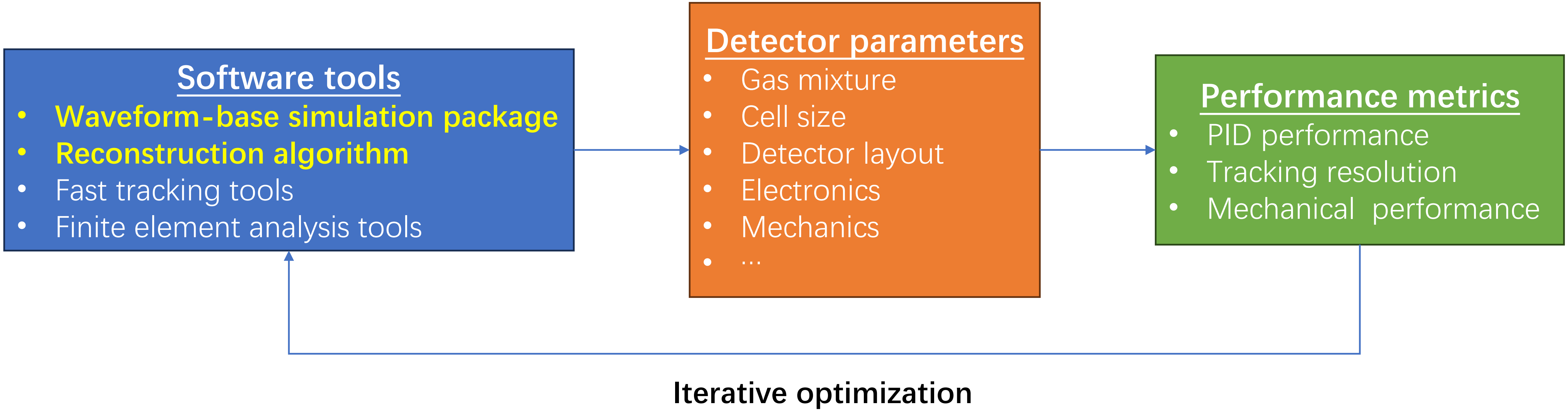
- **Challenges for large volume DC**
  - Electrostatic stability: L ~ 5m, need wire material studies

  → Finite element analysis

  - Data reduction: ~1 TB/s (Z-pole), need online data reduction
  - Power consumption/cooling design

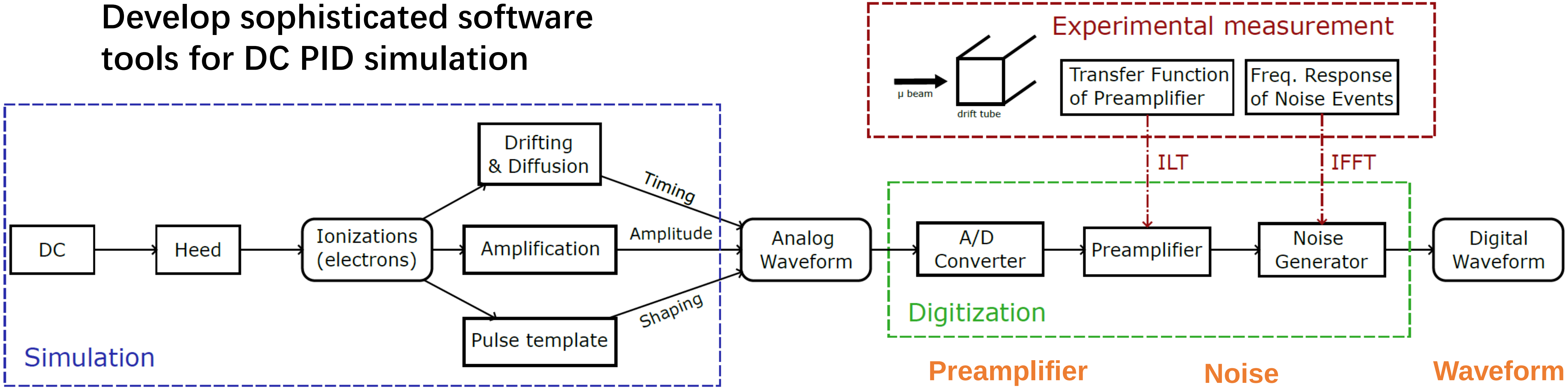
  → Need to do

Overall detector optimization flow

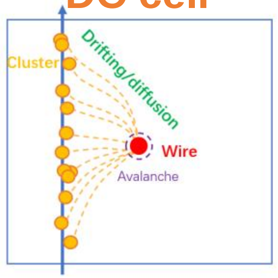


Waveform-based simulation

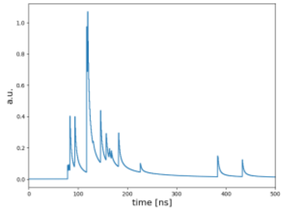
Develop sophisticated software tools for DC PID simulation



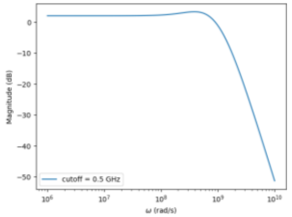
DC cell



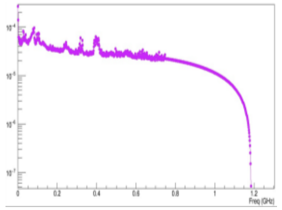
Induced signal



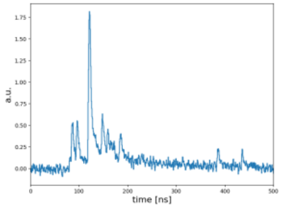
Preamplifier



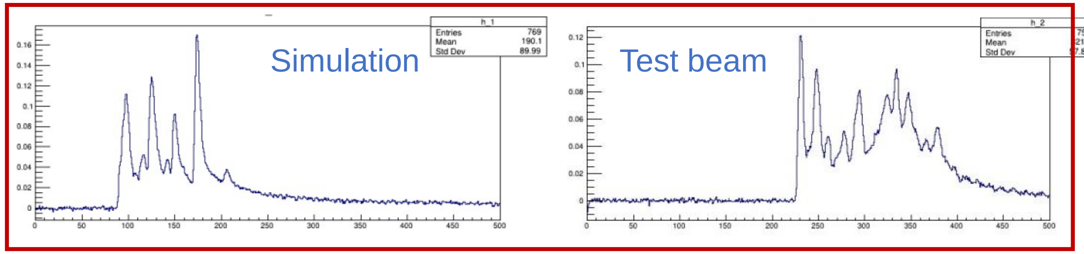
Noise



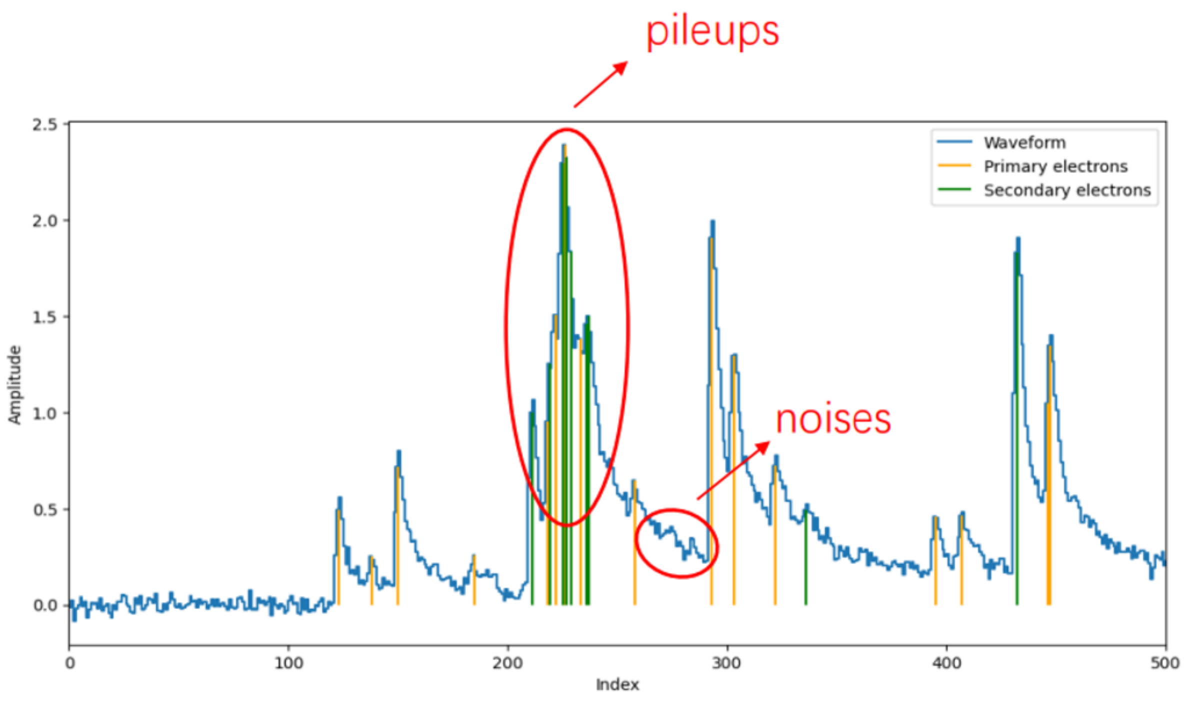
Waveform



Tuned MC is comparable to data



Traditional reconstruction algorithm



Simulated waveform of a DC cell. Orange lines are primary electrons. Green lines are secondary electrons.

Reconstruction: Each primary and secondary electrons forms a peak in the waveform. Need to determine the # of primary peaks.

Peak finding: Detect all electron peaks

- Taking 1st and 2nd order derivatives
- Peak detection by threshold passing

Clusterization: Merge electrons to form clusters

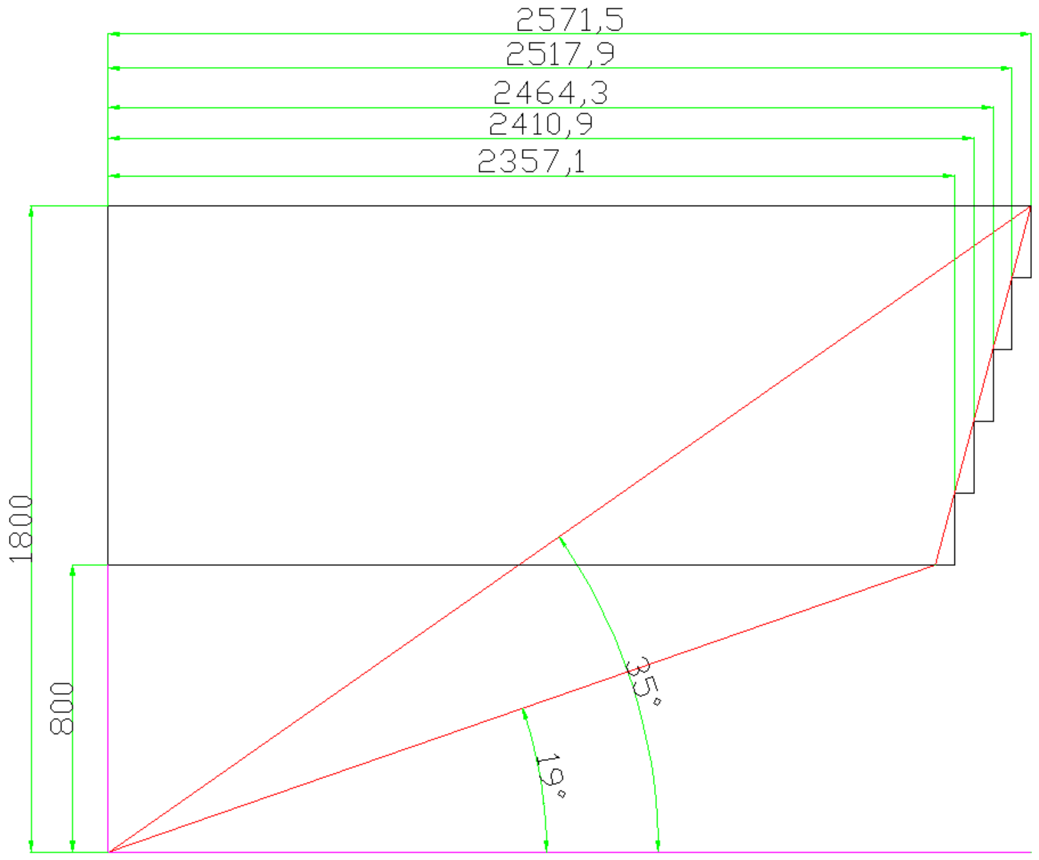
- Merge peaks within $[0, t_{cut})$
- The t_{cut} is related to diffusion

- **Pros:** Fast and easy to implement
- **Cons:** Suboptimal efficiency for highly pile-up and noisy waveforms ➡ **Deep learning**

Preliminary DC design

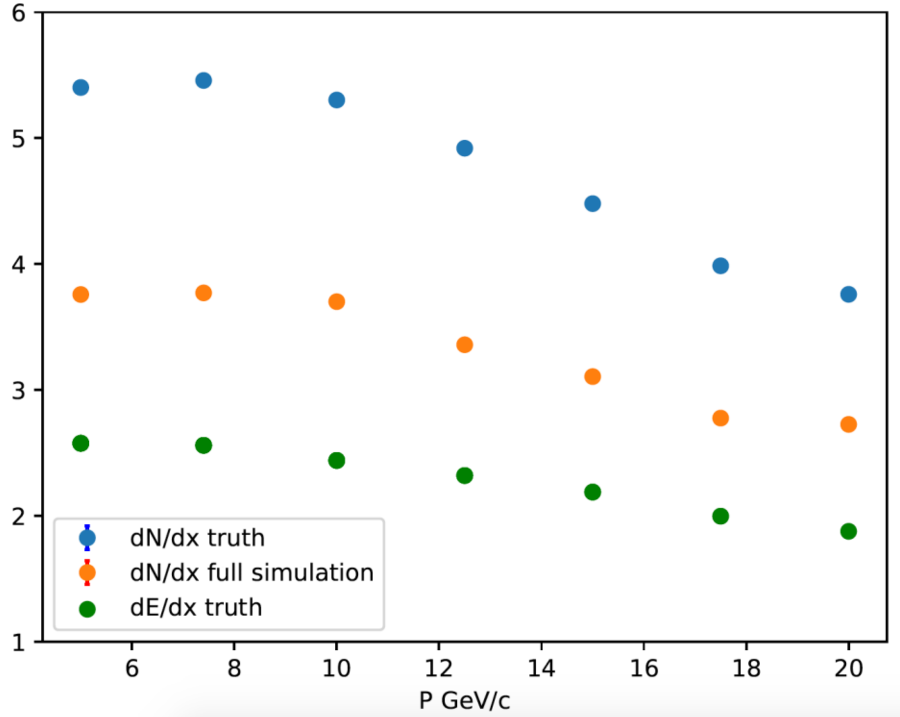
Optimized DC Parameters

DC Parameters	
Radius extension	800-1800 mm
Length of outermost wires（cosθ=0.82）	5143 mm
Thickness of inner CF cylinder	200 μm
Outer CF frame structure	Equivalent CF thickness: 1.63 mm
Thickness of end Al plate	35 mm
Cell size	18 mm × 18 mm
# of cells	24766
Ratio of field wires to sense wires	3:1
Gas mixture	He/iC_4H_{10}=90:10

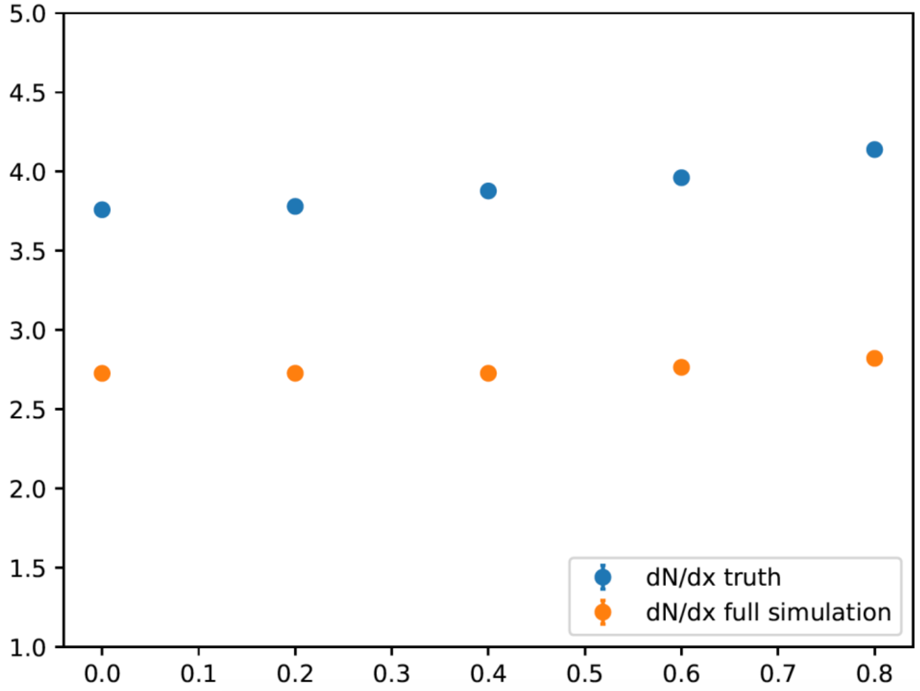


PID performance

K/π separation power vs P (1m track length, cosθ=0)



K/π separation power vs cosθ (P=20GeV/c)

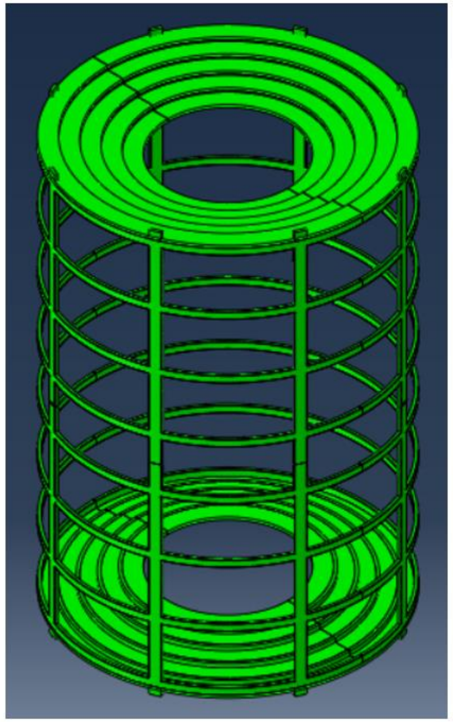


Separation power

$$S = \frac{\left| \left(\frac{dN}{dx}\right)_{\pi} - \left(\frac{dN}{dx}\right)_{K} \right|}{(\sigma_{\pi} + \sigma_{K})/2}$$

2σ K/π separation for 20 GeV/c tracks could be achieved

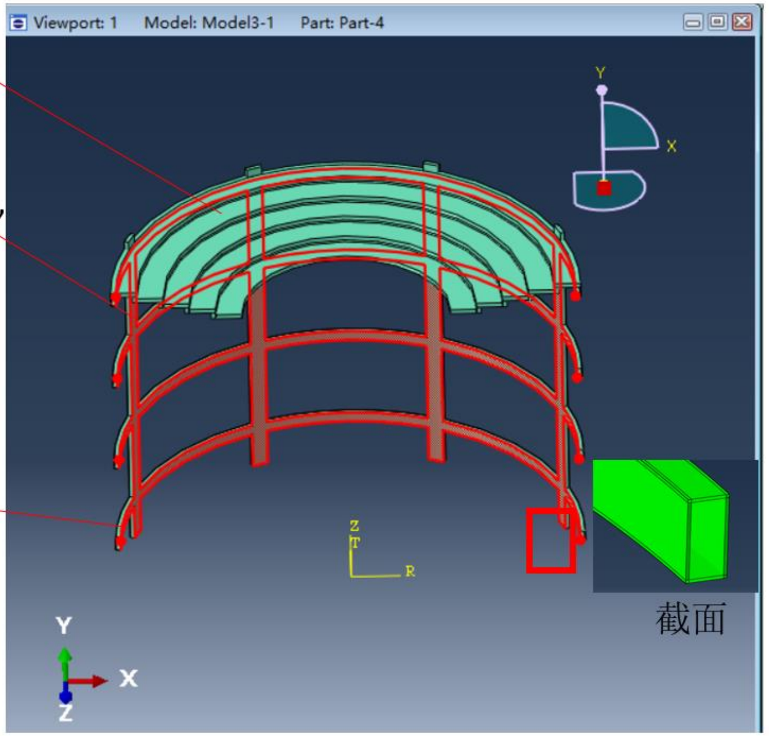
Mechanics with support structures



Al endplates : 35 mm

Longitudinal beam, Cross section: 122×40mm

Annular beam, Cross section: 80×40mm



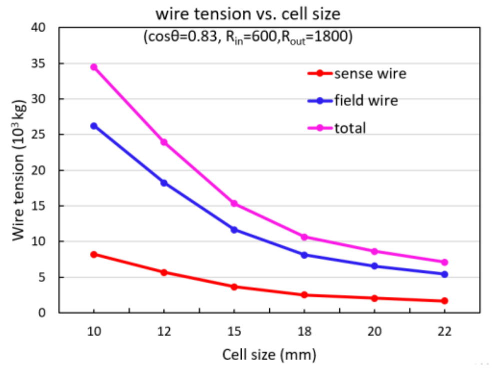
- Carbon fiber frame structure, including 8 longitudinal hollow beams and 8 annular hollow beams
- Thickness of inner CF cylinder: 200 μm/layer
- Effective outer CF frame structure: 1.63 mm
- Thickness of end Al plate: 35 mm

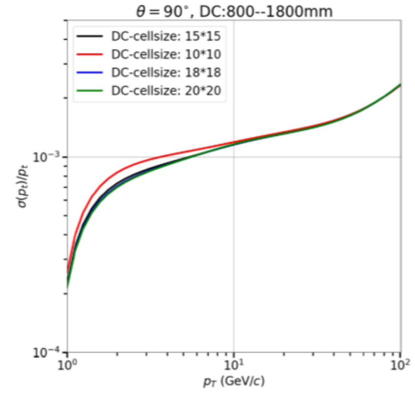
- **Mises stress: 70 MPa**
- **Principal stress: 33 Mpa**
- **Deformation: 0.8 mm**
- **Buckling coefficient: 17.2**

Preliminary calculation shows stable

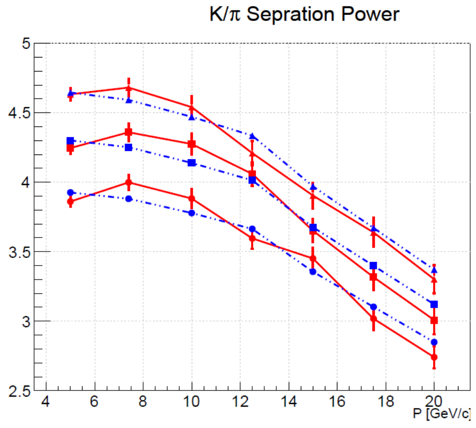
Further optimization considerations

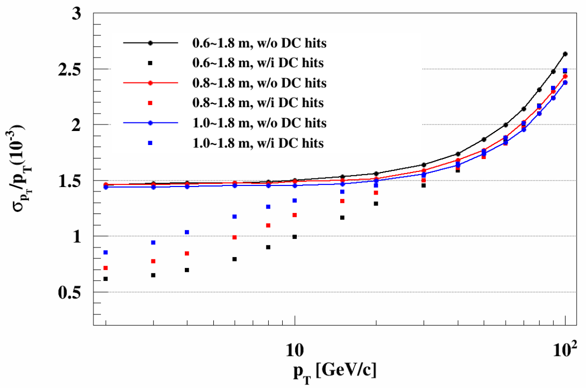
- **Cell size**
  - Cell size has little effect on PID. Large cell size is better for engineering and can reduce # of readout channels
  - Hybrid-cell-size: Reduce the cell size of the first 10 layers to achieve stable operation at high counting rates and minimize aging effects





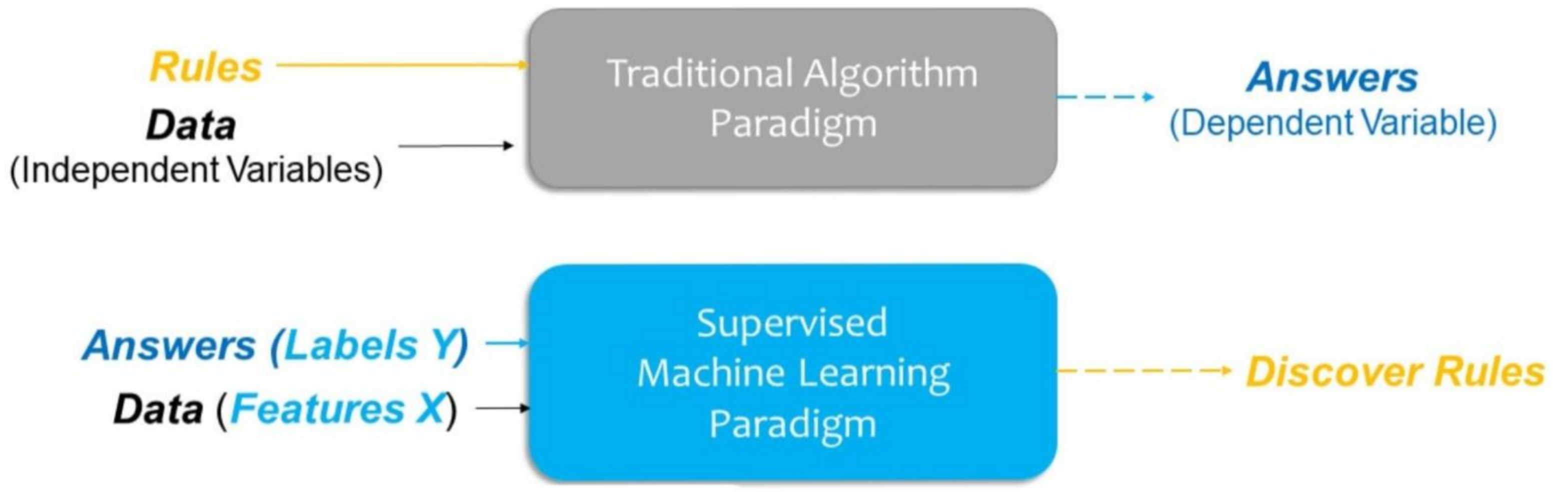
- **Inner radius**
  - Inner radius: 800 mm → 600 mm → 400 mm
  - K/π separation: 2.8σ → 3.1σ → 3.3σ @ 20 GeV/c
  - Smaller inner radius is better for PID and tracking resolution, but more challenge on engineering and aging effects





Reconstruction algorithm with deep learning

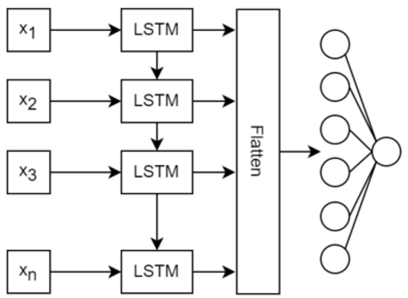
- **Traditional algorithm:**
  - Use partial information of the raw waveform
  - Require human input prior knowledge
- **Supervised learning could be more powerful** because
  - make full use of the waveform information
  - automatically learn characteristics of signals and noises from large labeled samples



Supervised model for simulated samples

Peak finding with LSTM

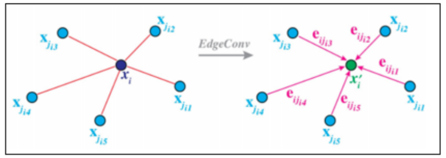
Why LSTM? ➔ Waveforms are time series



- Architecture: LSTM (RNN-based)
- Method: Binary classification of signals and noises on slide windows of peak candidates

Clusterization with DGCNN

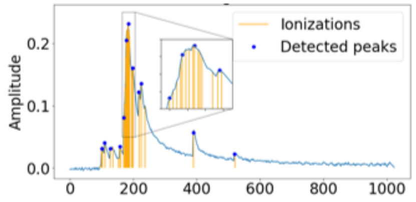
Why DGCNN? ➔ Locality of the electrons from the same primary cluster, perform massage passing through neighbor nodes in GNN



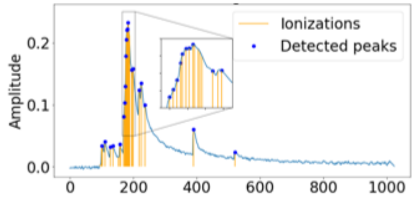
arXiv: 1801.07829

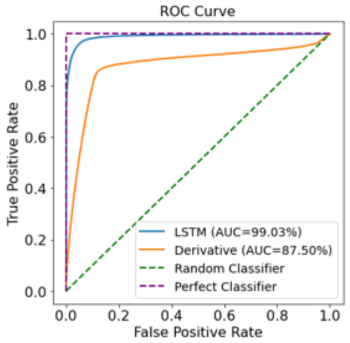
- Architecture: DGCNN (GNN-based)
- Method: Binary classification of primary and secondary electrons

Derivative-based method

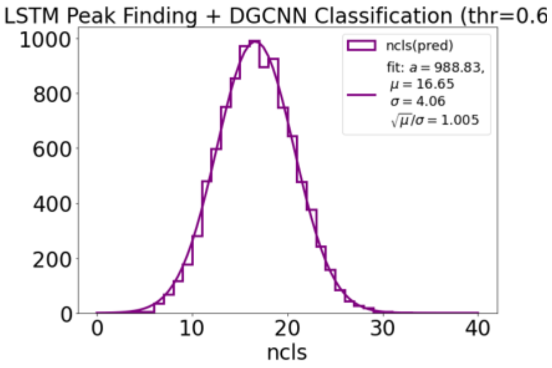


LSTM

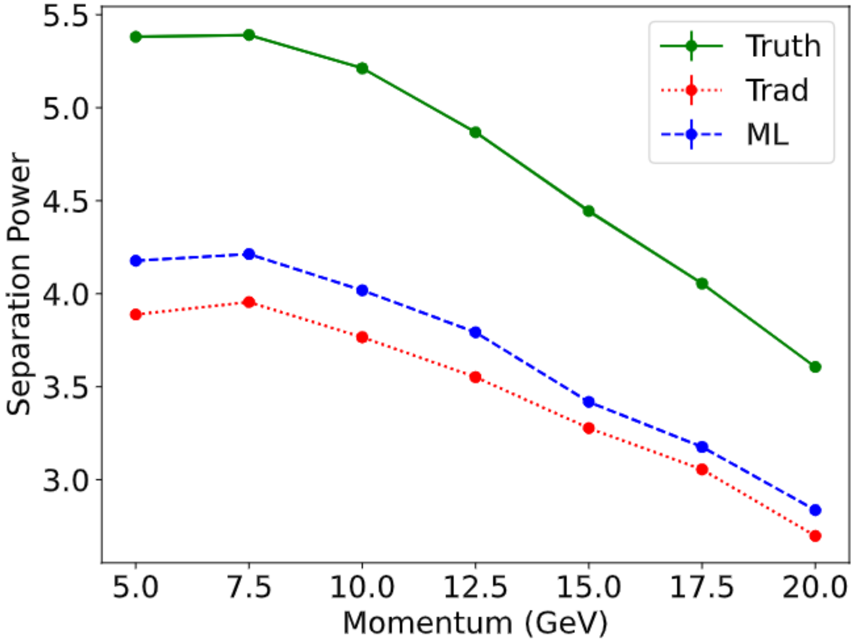




Peak finding: ML is better than derivative-based method



Peak finding + Clusterization: Very well Poisson-like distribution



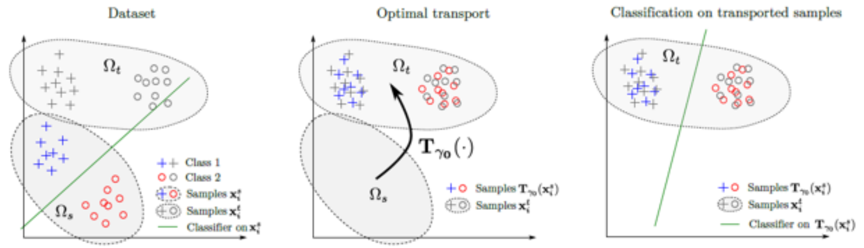
~10% improvement on K/π separation power with ML (equivalent to a detector with 20% larger radius)

Domain adaptation model for data samples

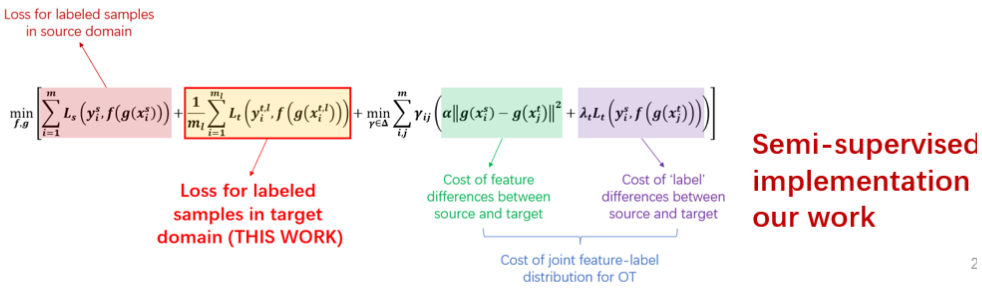
Main challenges:

- Discrepancies between data and MC
- Lack of labels in experimental data

➡ **Domain adaptation**



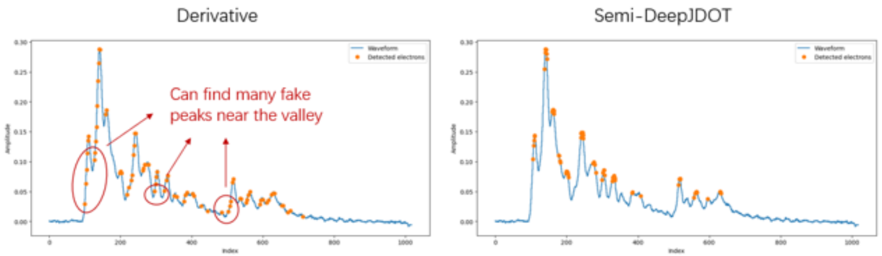
Align data/MC samples with Optimal Transport



$$\min_{f,g}\left[\sum_{i=1}^{m} L_s\left(y_i^s, f\left(g(x_i^s)\right)\right) + \frac{1}{m_l}\sum_{i=1}^{m_l} L_t\left(y_i^{t,l}, f\left(g(x_i^{t,l})\right)\right) + \min_{\gamma\in\Delta}\sum_{i,j}^{m} \gamma_{ij}\left(\alpha\left\|g(x_i^s) - g(x_j^t)\right\|^2 + \lambda_t L_t\left(y_i^s, f\left(g(x_j^t)\right)\right)\right)\right]$$

Semi-supervised implementation our work

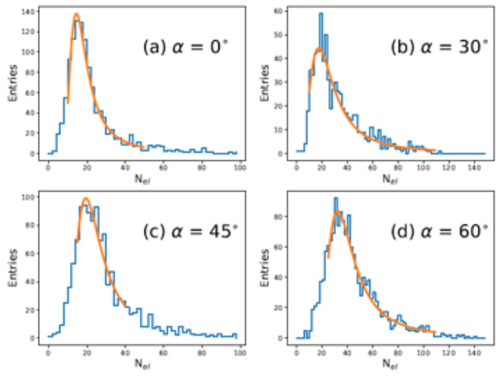
Single-waveform results between derivative alg. and DL alg.

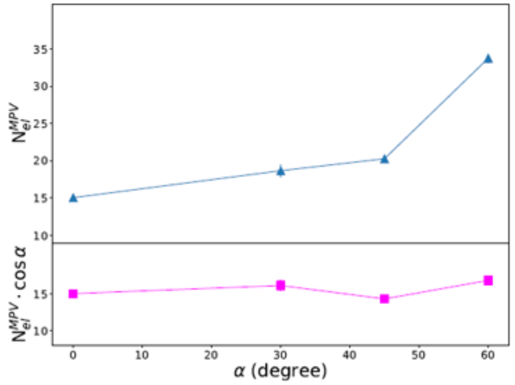


Note: Require similar efficiency for both cases

DL algorithm is more powerful to discriminate signals and noises

Multi-waveform results for samples in different angles





Scale w.r.t. track length

The algorithm is stable w.r.t. track length

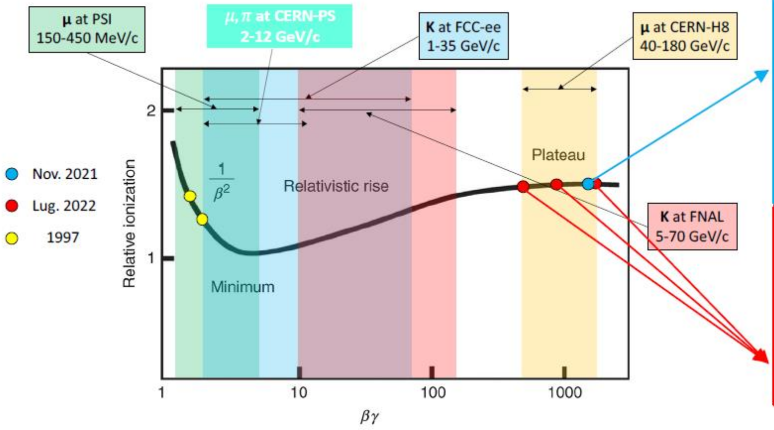
Test beam experiments at CERN

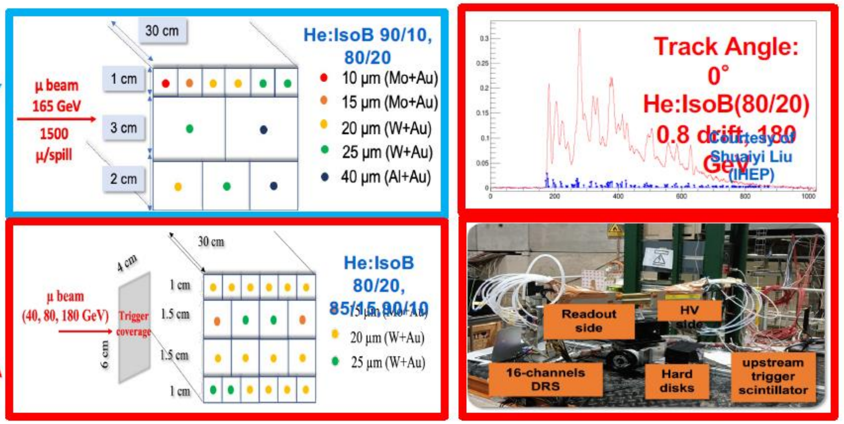
Beam tests organized by INFN group:

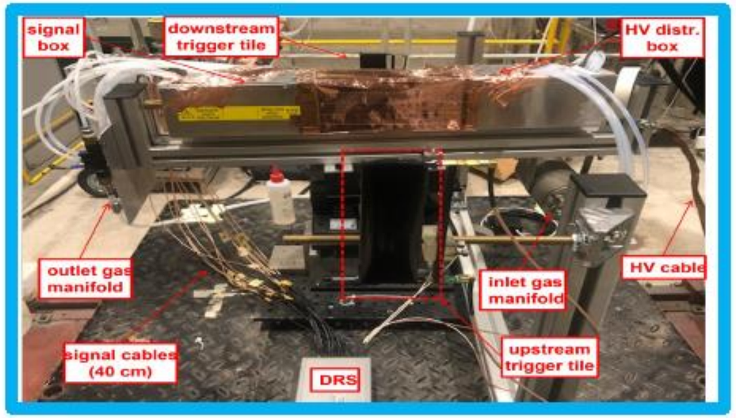
- Two muon beam tests performed at CERN-H8 (βγ>400) in Nov. 2021 and July 2022.
- A muon beam test (from 4 to 12 GeV/c) in 2023 performed at CERN.
- Ultimate test at FNAL-MT6 in 2024 with π and K (βγ = 10-14) to fully exploit the relativistic rise.

Contributions from IHEP group:

- Participate data taking and collaboratively analyze the test beam data
- **Develop the deep learning reconstruction algorithm**



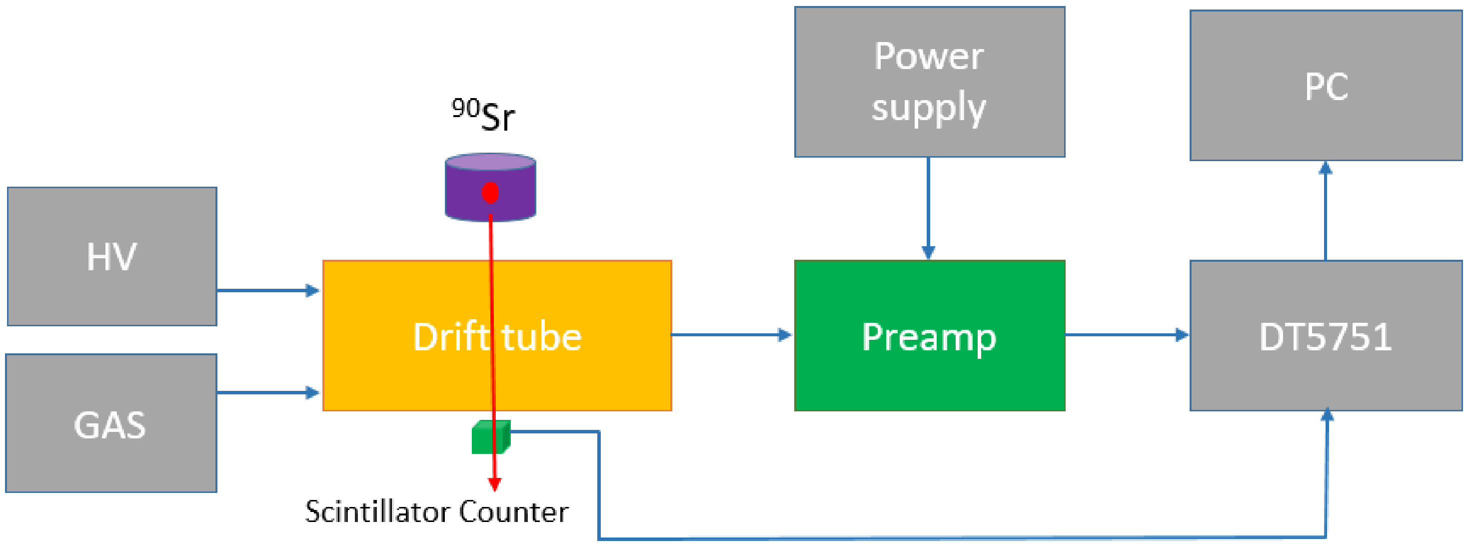




[See Nicola De Filippis's talk at the CEPC Workshop for details]

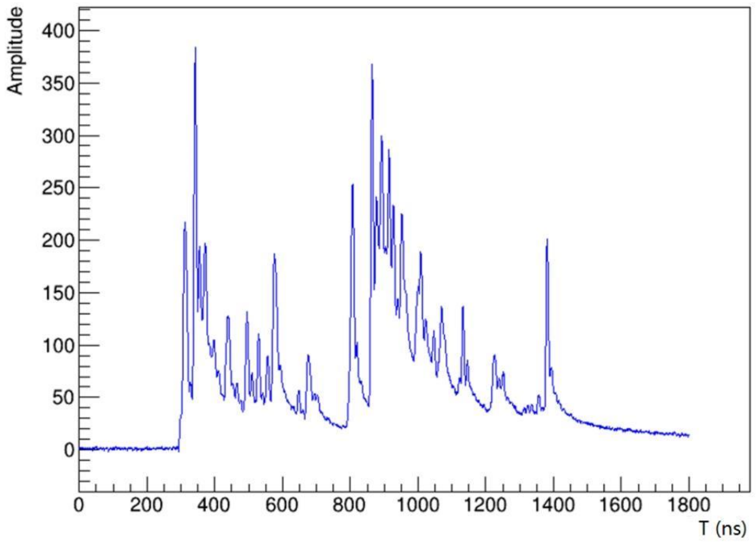
Prototype experiment at IHEP

Experiment layout



- Diameter of the tube: 30 mm
- Working gas: He/iC_4H_{10}=90:10

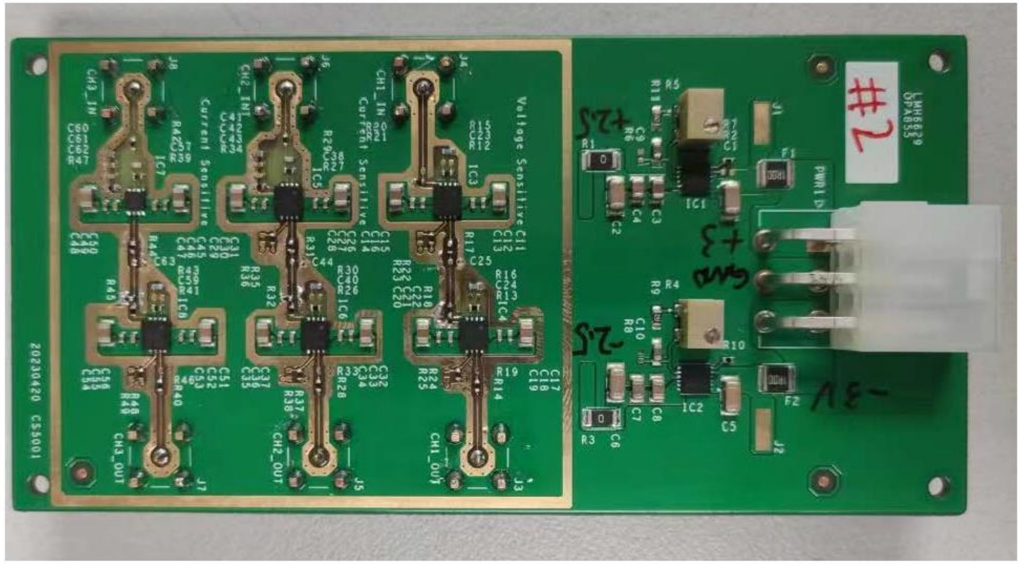
Waveform with Sr-90 β source

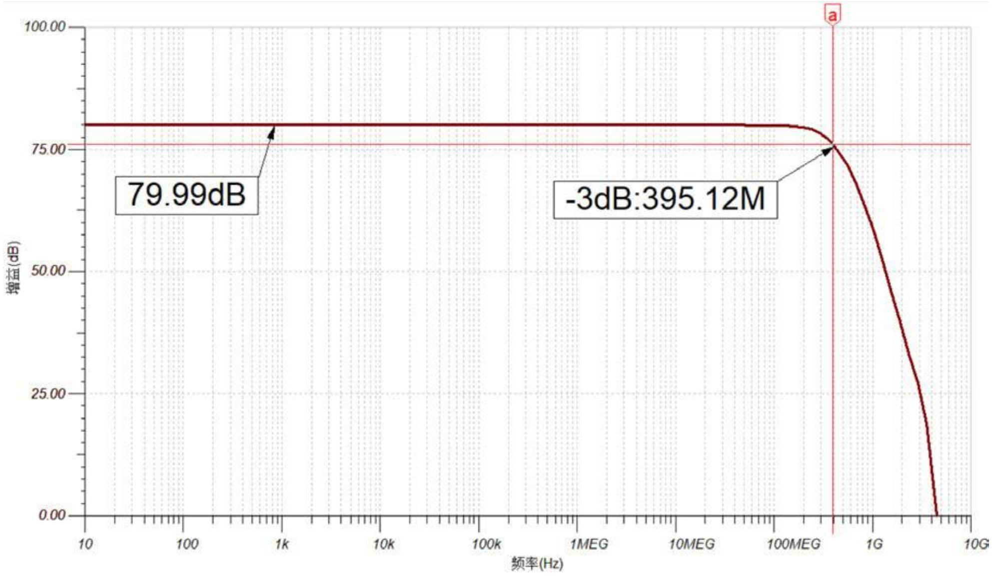


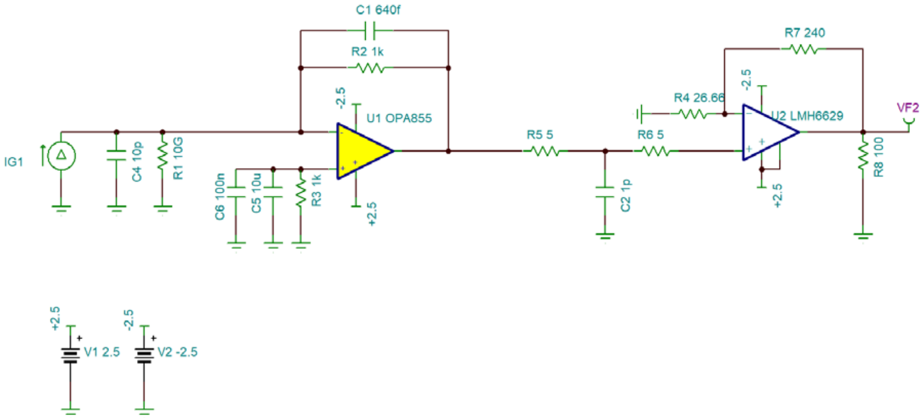
CC signal observed with

- **low noise**
- **high bandwidth**
- **fast risetime: ~ns**

Electronics development







- High bandwidth current sensitive preamplifiers based on LMH6629 have been designed and developed
- Tested with detector prototype and digitizer (DT5751) with 1 GHz sampling rate

Summary

- **Preliminary DC design**
  - PID performance: Close to 3σ K/π separation at 20 GeV/c for 1m track length
  - Mechanical stability: Stable with FEM simulations
- **Reconstruction**
  - 10% improvement on K/π separation for supervised model
  - Domain adaption model for experimental data
- **Experiments**
  - Fast electronics development and prototype test at IHEP: observe CC signals
  - International collaboration on test beam experiments
- **Plans**
  - Fine detector optimization
  - Optimize deep learning algorithm and FPGA implementation
  - Electronics developments and experiments
  - Mechanical design and tests
  - Physics benchmarks

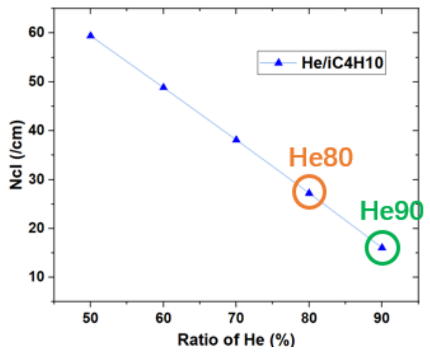
Backup

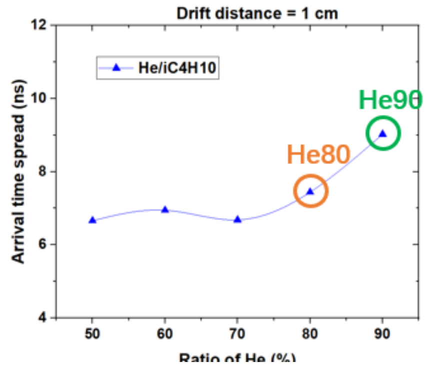
Requirements of detector and key technologies

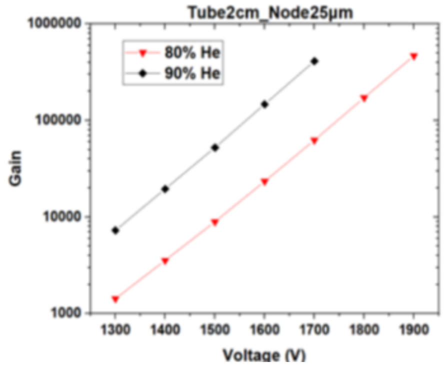
Sub-detector	Key technology	Key Specifications
Silicon vertex detector	Spatial resolution and materials	$\sigma_{r\phi} \sim 3\ \mu\text{m}$, $X/X_0 < 0.15\%$ (per layer)
Silicon tracker	Large-area silicon detector	$\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1\times10^{-3}}{p\times\sin^{3/2}\theta}(\text{GeV}^{-1})$
TPC/Drift Chamber	Precise dE/dx (dN/dx) measurement	Relative uncertainty 2%
Time of Flight detector	Large-area silicon timing detector	$\sigma(t) \sim 30$ ps
Electromagnetic Calorimeter	High granularity 4D crystal calorimeter	EM energy resolution $\sim 3\%/\sqrt{E(\text{GeV})}$ Granularity $\sim 2 \times 2 \times 2\ \text{cm}^3$
Magnet system	Ultra-thin High temperature Superconducting magnet	Magnet field $2-3$ T Material budget $< 1.5X_0$ Thickness < 150 mm
Hadron calorimeter	Scintillating glass Hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(\text{GeV})}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(\text{GeV})}$

Gas mixture

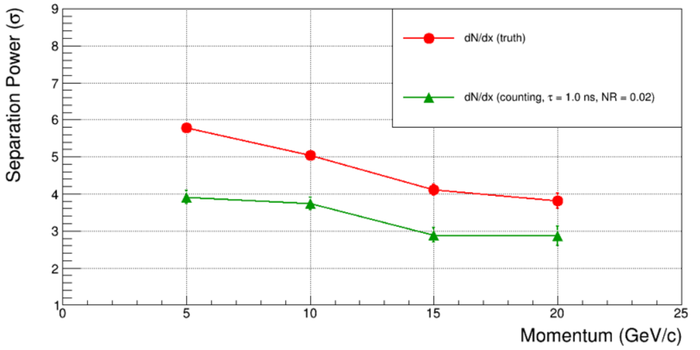
- **Gas mixture choice: He + C_4H_{10}**







He 90% + iC_4H_{10} 10%, L = 1m, NR = 0.02，1x1cm cell



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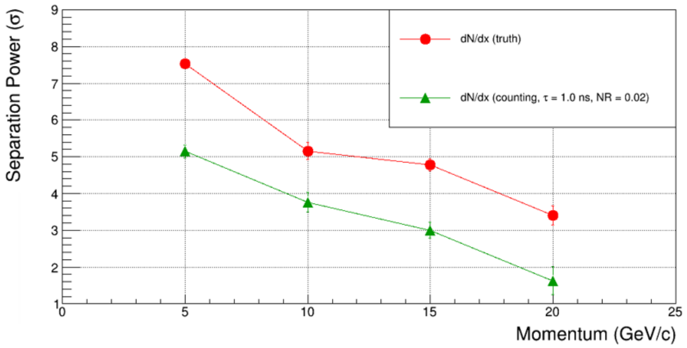
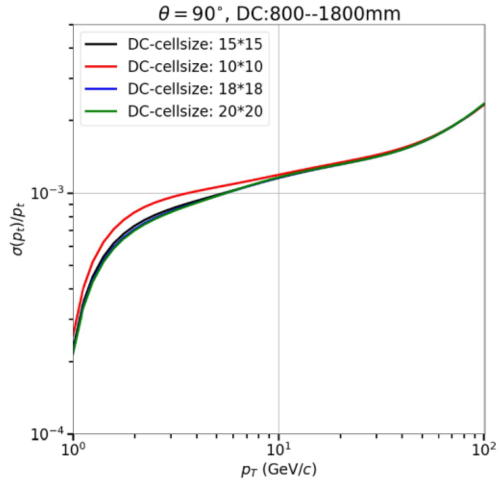


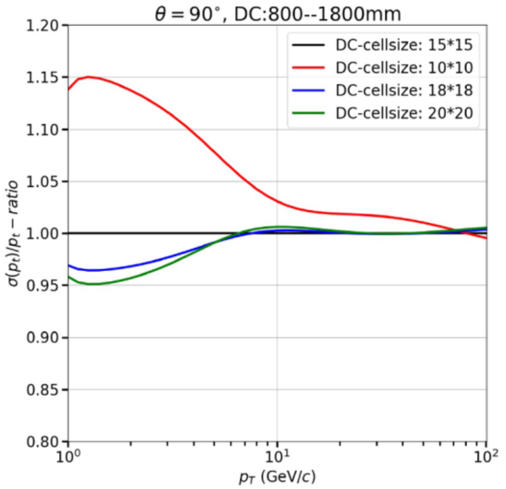
Gas property for CC:

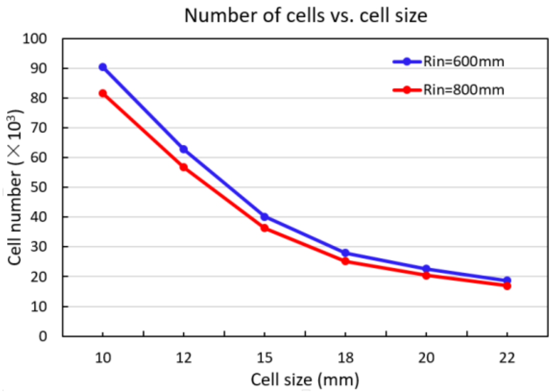
- Small ρ_{cl} ➔ less statistics, large time separation
- Slow v_d ➔ large time separation
- Small σ_d ➔ less likely double-counting

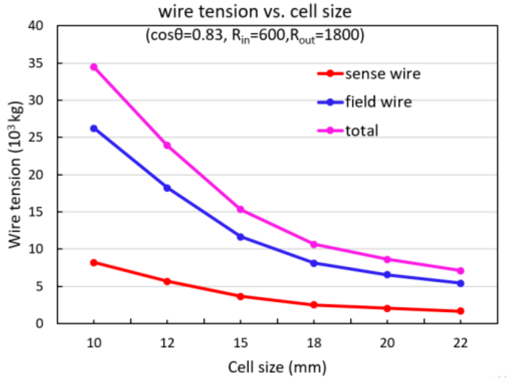
- **He 90% + iC_4H_{10} 10% is better for high momentum**

Cell size

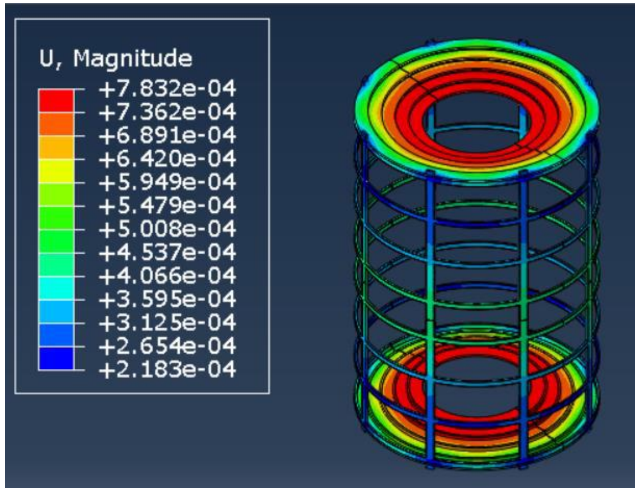








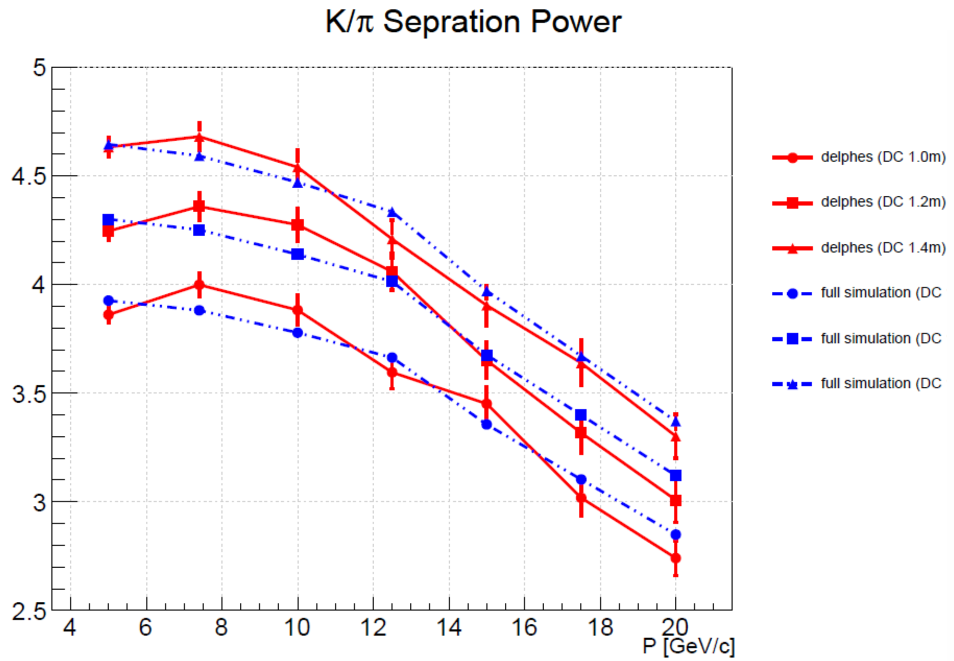
- Increasing the cell size has little effect on the PID performance.
- The number of wires can be reduced, hence the production difficulty, the number of readout channels, and the material of the supporting structure (mostly at the outer cylinder).
- Hybrid-cell-size could be possible. (e.g. reduce the size of the first 10 layers)

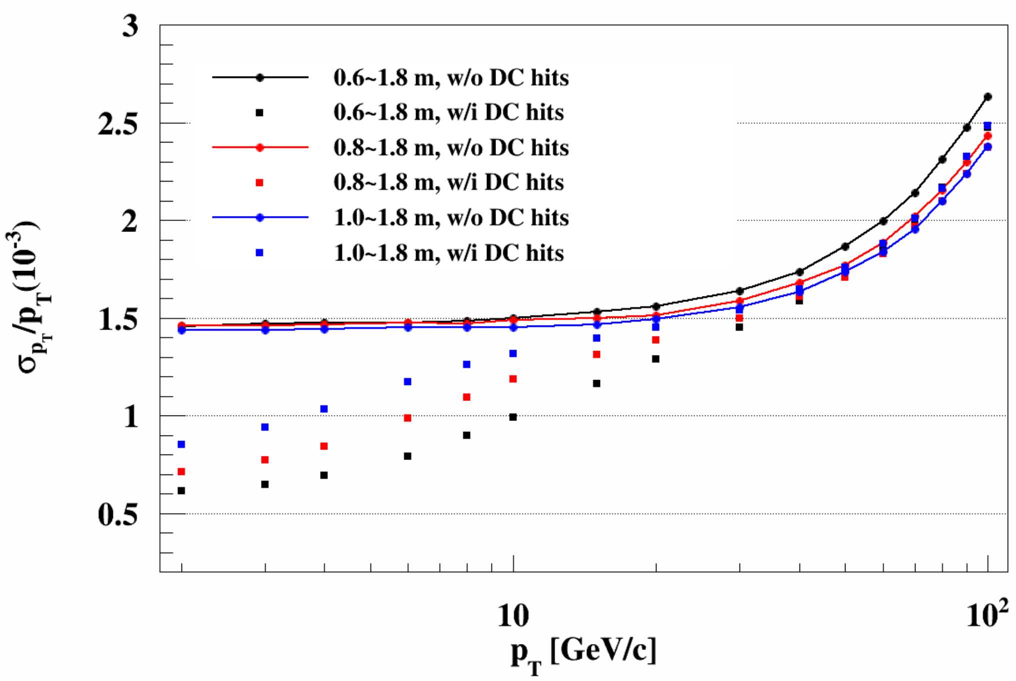


Finite element analysis

With cell size of 18x18 mm^2, field (sense) wire with Φ=60 (20) μm, wire tension ~ 9000 kg which satisfies stability condition

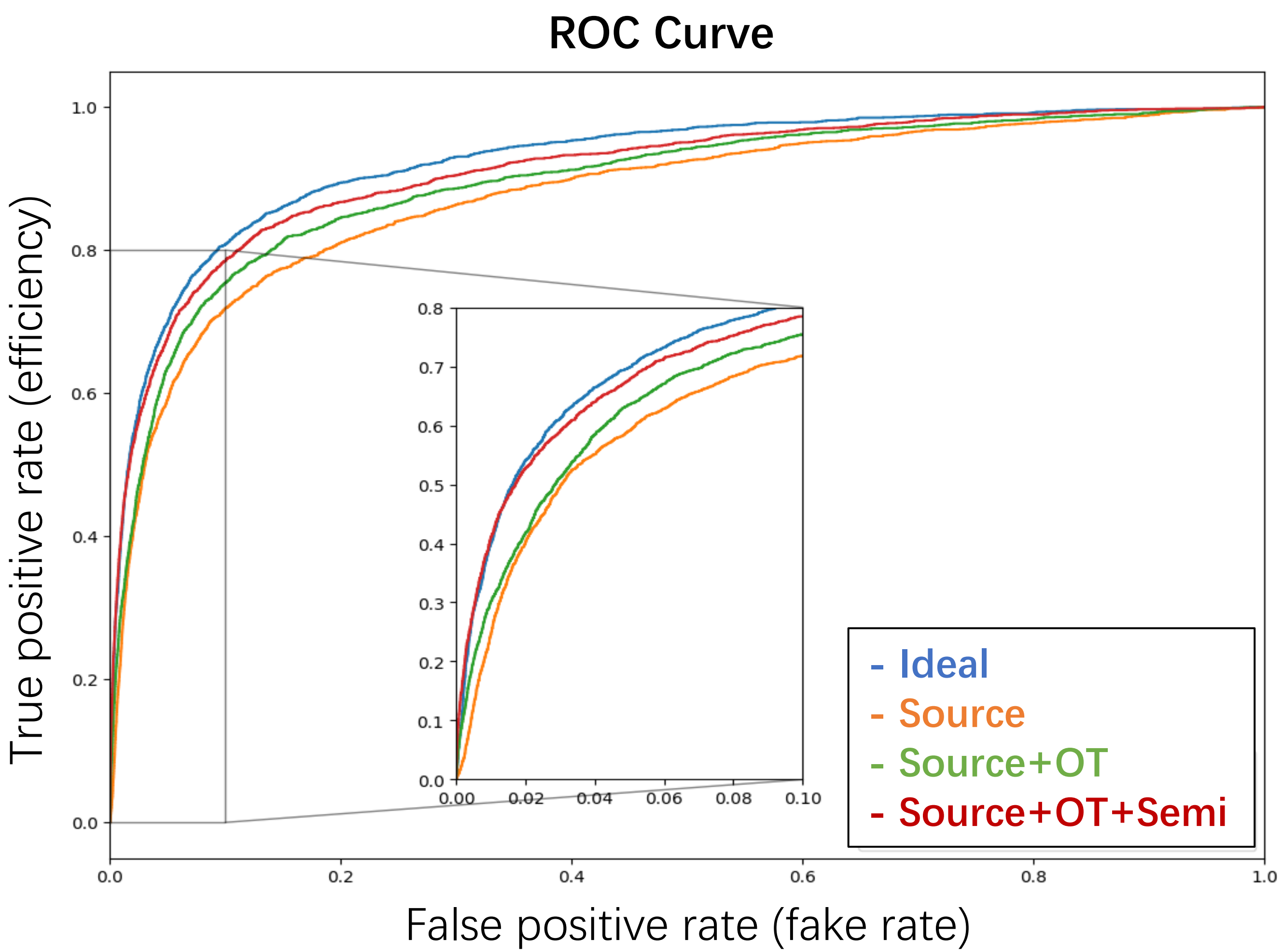
Inner radius





- Large thickness is better for PID ➔ From 2.8σ to 3.1σ even 3.3σ @ 20 GeV/c
- Smaller inner radius is better for tracking resolution, but more challenge on engineering and more beam backgrounds

Numeric experiment



Numeric experiment with pseudo data:

- Use labels in pseudo data to evaluate

Model	AUC	pAUC (FPR<0.1)
Ideal (supervised)	0.926	0.812
Source (baseline)	0.878	0.749
Source + OT	0.895	0.769
Source + OT + Semi (Semi-supervised DA)	0.912	0.793

Validation: Performance of Semi-DeepJDOT model is very close to the ideal model (supervised model)

Mechanicals: Wire tension

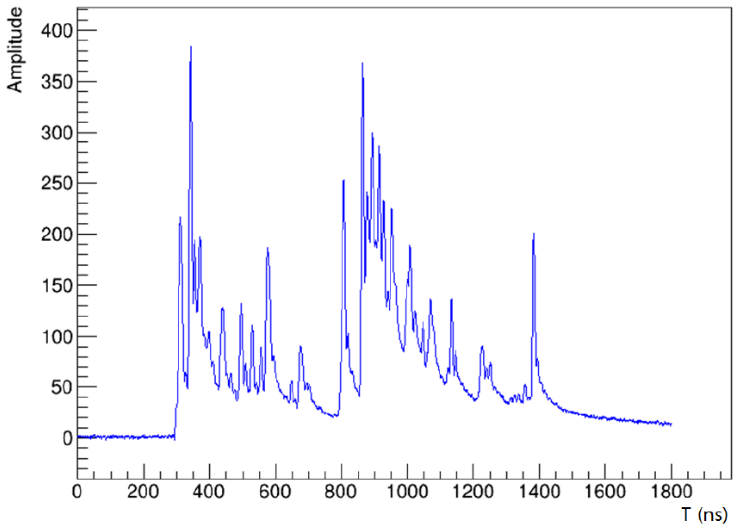
- ✓ Diameter of field wire (Al coated with Au) : 60 µm
- ✓ Diameter of sense wire (W coated with Au): 20 µm
- ✓ Sag = 280 µm

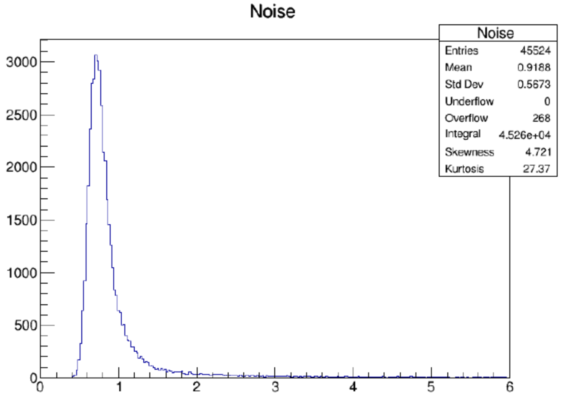
Step	cell number /step	length	single sense wire tension (g)	Single field wire tension (g)	total tension /step (kg)
1	3417	4715	60.15	92.42	1153.08
2	4185	4822	62.91	96.66	1477.02
3	4953	4929	65.74	101.00	1826.47
4	5721	5036	68.62	105.44	2202.24
5	6489	5143	71.57	109.96	2605.11
total	**24766**				**9263.92**

Meet requirements of stability condition: $T > (\frac{VLC}{d})^2/(4\pi\varepsilon_0)$

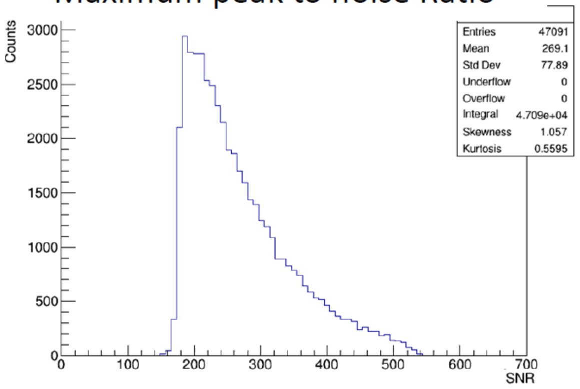
Waveforms from prototype tests

Waveform with Sr-90 β source

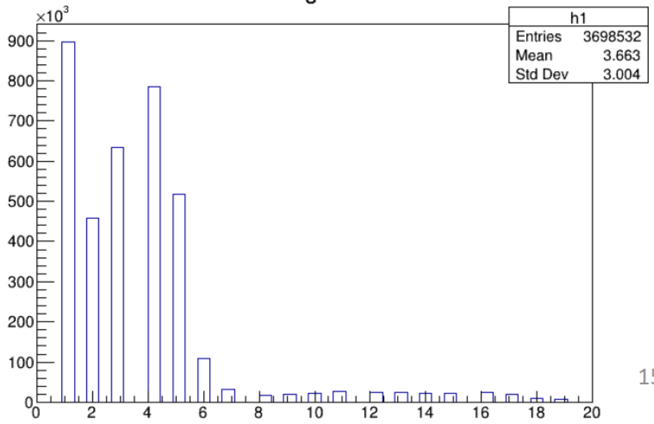




Maximum peak to noise Ratio



Rising Time



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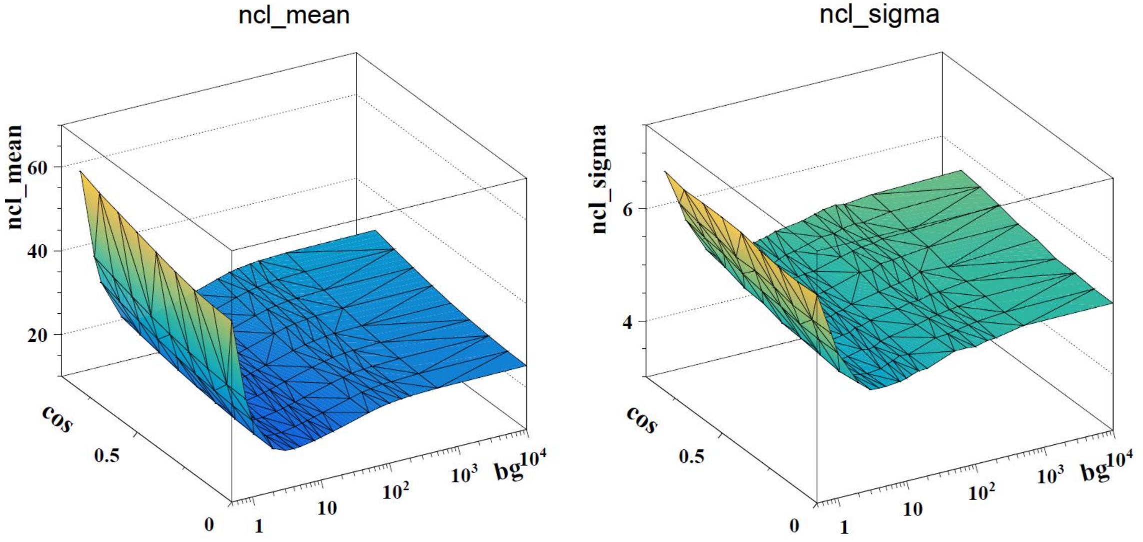
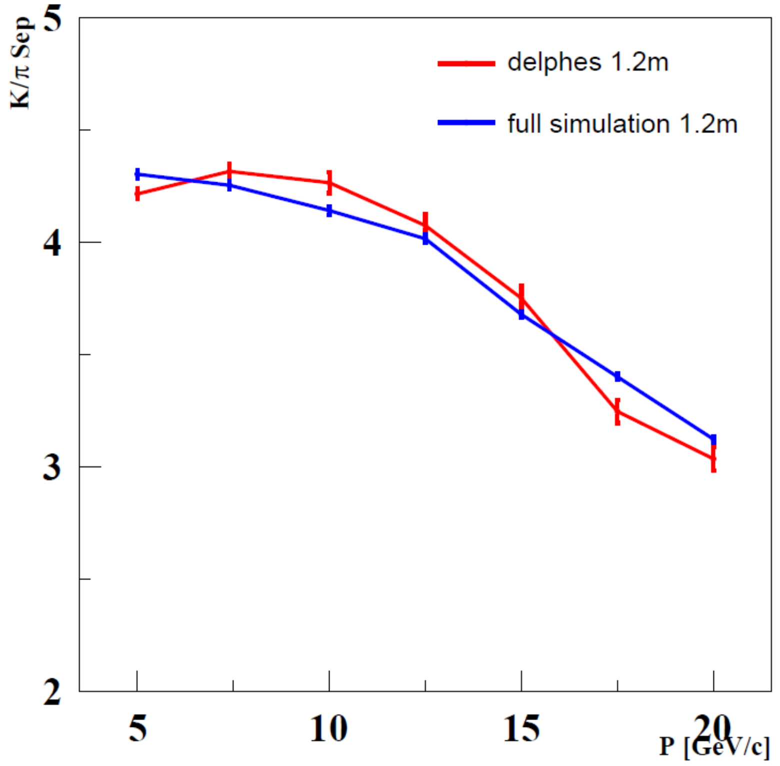
- Test results show
  - low noise
  - high bandwidth
  - Rise time of peak: a few nanoseconds

Physics study with Delphes

- **Delphes: A C++ framework, performing a fast multipurpose detector response simulation**
  - $10^2 \sim 10^3$ faster than the fully GEANT-based simulations
  - Sufficient and widely used for phenomenological studies
- **Develop dedicated PID modules (CC and TOF) and perform quick physics studies**



K/π separation power

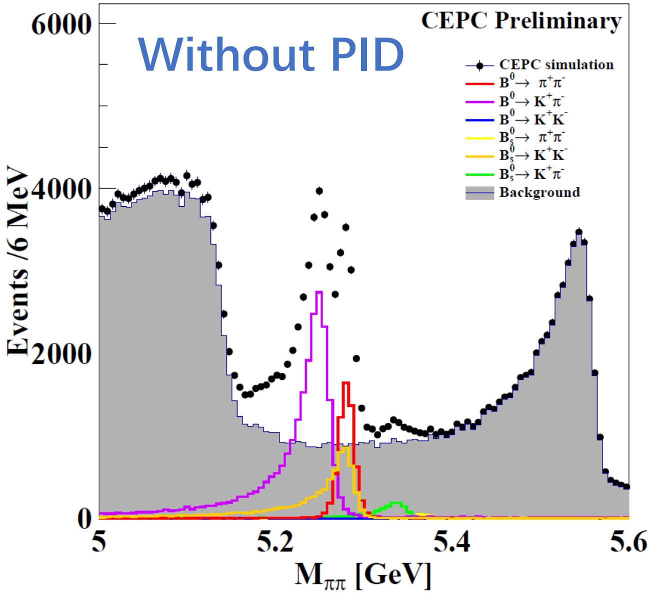


Good consistent to full simulation

Study of $\mathbf{B^0_{(s)} \to h^+h'^-}$

- **Motivation**
  - Rich physics programs in $B^0_{(s)} \to h^+h'^-$ decays
    - Time-dependent asymmetry, direct CP violation, lifetime measurement, ⋯
  - Good test bed to study impact of PID in flavor physics
  - Explore physics potential of Tera-Z

- **Significantly improved SNR with PID**
- **More detailed studies ongoing**



With PID